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Cambrian–Ordovician conodonts from slump deposits of the Argentine Precordillera: new insights into its passive margin development

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Abstract – The Los Sombreros Formation represents the western continental margin slope deposits of the Argentine Precordillera, a sub-terrane accreted to Gondwana as part of the Cuyania Terrane in early Palaeozoic times. The age of these gravity-driven deposits is controversial and, therefore, a precise biostratigraphic scheme is essential to reveal the evolution of the continental margin. New conodont samplings along with sedimentological and structural analysis carried out in the Los Sombreros Formation in the La Invernada Range provide clues to its depositional framework. The sedimentary succession is made up of dominantly calciturbidites, carbonate breccias and conglomerates, along with mudstones that represent the pelagic/hemipelagic background sedimentation. It displays hectometric to outcrop-scale slump folds with variable hinge-line orientations and pinch-and-swell structures, evidencing soft-sediment deformation, consistent with a slope to base-of-slope setting. Three limestone samples from this succession include conodonts referable to the pandemic *Hirsutodontus simplex* Subzone of the *Cordylodus intermedius* Zone (upper Furongian, Cambrian) and from the *Macerodus dianae* Zone (upper Tremadocian, Ordovician), implying that a slope connected the shallow-water shelf with a deep-water (oceanic) basin at least since late Cambrian times. The conodont faunas show affinities to coeval assemblages from outer shelf and slope environments around Laurentia yet they are not conclusive to postulate a geographic origin for the Precordillera. The thermal alteration of the conodonts is consistent with sedimentary burial and nappe stacking in this sector of the Precordillera.

Keywords: conodont, slope facies, slump, Los Sombreros Formation, Argentine Precordillera, Cambrian, Ordovician.

1. Introduction

In the external zone of the Andean orogen, the Argentine Precordillera records a series of tectonostratigraphic events related to the building of Gondwana during early to middle Palaeozoic times (e.g. Cawood, 2005; Rapela *et al.* 2016). Eastern, Central and Western domains have classically been distinguished after their structural and stratigraphic features (Ortiz & Zambrano, 1981; Baldis *et al.* 1982). The Eastern and Central Precordillera involve a large passive-margin carbonate platform, Cambro-Ordovician in age, which is overlain by Middle Ordovician siliciclastic foreland-basin deposits that reach up to the Devonian Punta Negra Formation. Conversely, the Western Precordillera exhibits a deep-water succession, with ocean-floor sedimentary rocks containing pillow lavas and mafic–ultramafic bodies in the westernmost sections.

The transition between the Central and Western Precordillera is represented by the disorganized deposits of the Los Sombreros Formation (Cuerda, Cingolani & Varela, 1983; Banchig, Keller & Milana, 1990) and the Corralito Formation (Furque & Caballé, 1988; Furque *et al.* 1990), recording the slope of a continental margin. However, the complex structure and the scarcity of fossils challenge against a precise depositional scheme, whilst Ordovician and Devonian ages have been proposed for the Los Sombreros Formation (e.g. Benedetto & Vaccari, 1992; Voldman, Albanesi & Ramos, 2009; Peralta, 2013). For instance, Peralta (2013) considered that all the disorganized deposits slid in Devonian times, after sedimentation of the Punta Negra Formation. Thus, constraining the spatio-temporal framework of the mélanges is essential for understanding the geotectonic evolution of the passive continental margin of the early Palaeozoic Precordillera.

In the present study, new conodont findings along with structural, stratigraphic and sedimentological data

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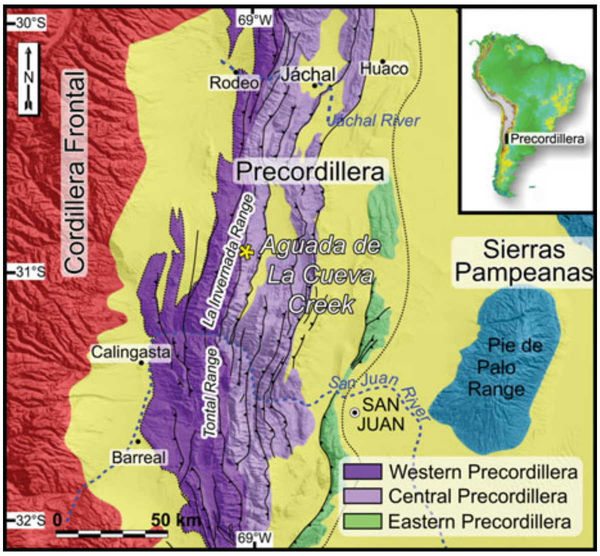

Figure 1. (Colour online) Location map of the Argentine Precordillera fold-and-thrust belt showing the studied locality and the western, central and eastern morphostructural domains. Base image derived from Shuttle Radar Topography Mission (SRTM).

for the Los Sombreros Formation in the La Invernada Range are presented. The record of the *Hirsutodontus simplex* Subzone of the *Cordylodus intermedius* Zone (upper Furongian, Cambrian) and the *Macerodus dianae* Zone (upper Tremadocian, Ordovician) in gravity-flow deposits with synsedimentary deformation features suggests the existence of a slope in late Cambrian – Early Ordovician times. Moreover, the defined high-resolution conodont biostratigraphy improves the intrabasinal correlation with the Precordilleran carbonate platform as well as with other regions of the world.

2. Geological setting

The Argentine Precordillera of La Rioja, San Juan and Mendoza provinces is a *c*. 80 km wide foreland fold-and-thrust belt that involves Palaeozoic to Cenozoic rocks, which extends between 29º and 33º S in the Andean foothills above the shallow subduction segment of the Nazca plate (Heim, 1952; Allmendinger *et al.* 1990; Gosen, 1992; Ramos, Cristallini & Pérez, 2002) (Fig. 1). The Precordilleran Cambrian–Ordovician carbonate platform sequence is unique to South America and makes up part of a larger region of the Andean foothills of western Argentina that is referred to as the Cuyania composite terrane (Ramos, 1995).

At the continental slope and rise, to the west of the Precordilleran carbonate platform, the Los Sombreros mélange is a mudstone-dominated deep-water disorganized unit, containing a diverse array of rocks derived from the platform, the slope and the basement. These rocks include arkosic sandstones, megabreccias, conglomerates with well-rounded basement-derived metamorphic and igneous pebbles to boulders, thin-bedded fine-grained limestones, carbonate breccias and blocks up to several hectometres in size of lower Cambrian to Lower Ordovician limestones displaying platform facies not represented elsewhere (e.g. Bordonaro, 2003).

The Los Sombreros Formation displays ubiquitous extensional structures that result in block-in-matrix fabric in some places as a consequence of submarine sliding (Alonso *et al*. 2008). The main outcrop belt of the mélange extends along the eastern flank of the Tontal Range (Fig. 1), where the formation is more than 1000 m thick in the Seca Creek type section (Cuerda, Cingolani & Varela, 1983; Cuerda *et al.* 1986). The outcrops continue patchily to the north up to the Jáchal River area (Benedetto & Vaccari, 1992), whereas its southern prolongation is represented by the Estancia San Isidro Formation in Mendoza, which exhibits giant Cambrian limestone blocks enclosed in a green shaly matrix of Darriwilian age (Keller, 1999; Heredia & Beresi, 2004; Ortega *et al*. 2007). Thus, the slope facies of the Precordillera extends over 300 km with N–S orientation (Fig. 1).

3. Previous biostratigraphic studies of the Los Sombreros Formation

The Los Sombreros Formation was originally referred to the Lower Ordovician Series based on graptolite records from its lower third (Cuerda *et al.* 1985). Later trilobite findings revealed the presence of lower and middle Cambrian rocks (Bordonaro & Baldis, 1987; Bordonaro & Banchig, 1990), interpreted as outer-platform resedimented blocks in a Lower – Middle Ordovician succession with autochthonous conodonts and graptolites (Benedetto & Vaccari, 1992; Bordonaro, 2003). Lehnert (1994) described the first conodont assemblage of the *Cordylodus proavus* Zone (upper Furongian) in the Precordillera, from outcrops of the Los Sombreros Formation in the Tontal Range. The conodont association includes *Cordylodus primitivus* Bagnoli, Barnes & Stevens, *Cordylodus proavus* Müller and *Eoconodontus notchpeakensis* Miller. These conodont elements derive from a calcisiltite lens that overlies shales with graptolite specimens that demonstrate its allochthonous character.

Albanesi, Ortega & Hünicken (1995) proposed that the conformable stratigraphic contact between the Los Sombreros Formation and the overlying Yerba Loca Formation at Ancaucha Creek, 10 km northwest of Jáchal city, is early Darriwilian in age. They determined that the top of the Los Sombreros Formation at this locality is lower Darriwilian at the most, by considering the presence of the index conodont *Baltoniodus clavatus* Stouge & Bagnoli from the basal beds of the Yerba Loca Formation and the absence of the key species *Paroistodus horridus* (Barnes & Poplawski), which appears *c*. 40 m above the Yerba Loca base.

Further fossil findings include upper Cambrian, Tremadocian, Floian and Darriwilian conodont faunas (Voldman, Albanesi & Ramos, 2009; Voldman *et al.* 2014) as well as graptolites referable to the uppermost Tremadocian, Floian and Sandbian stages (e.g. A. L. Banchig, unpub. Ph.D. thesis, Univ. Nacional San Juan,

Figure 2. (Colour online) Geological map of the study area with fossiliferous sampling points.

1995; Banchig & Moya, 2002; Ortega *et al.* 2014). Additionally, Astini, Thomas & Yochelson (2004) identified the enigmatic fossil *Salterella maccullochi* (Murchison) in the Ancaucha Olistolith of the Los Sombreros Formation, composed of inner-shelf deposits that they interpreted as lower Cambrian synrift strata.

4. Study area and methods

The La Invernada Range constitutes a critical region to investigate the architecture and kinematic development of the disorganized deposits of the Los Sombreros Formation. This range lies to the north of the Tontal Range, extending for *c.* 60 km with a N–S trend (Fig. 1). It displays E-verging thrusts and related folds, involving a lower Palaeozoic succession that also includes the Siluro-Devonian mélange deposits of the Corralito Formation, which crop out exclusively in this range. In order to determine the age of the Los Sombreros Formation at the Aguada de La Cueva Creek section (Fig. 2), nine limestone samples (14 kg in total) were collected and processed following the standard techniques to recover conodont elements (Stone, 1987). Three samples were productive, yielding 80 specimens that are housed under the repository codes CORD-MP 50734 to 50814 in the Museo de Paleontología, Facultad de Ciencias Exactas, Físicas y Naturales, Universidad Nacional de Córdoba, Argentina. Field work also included structural mapping and stratigraphic and sedimentological studies, during which kinematic data were acquired and rocks were described in terms of their bedding and lithology and sampled for thin-section preparation.

5. Results

5.a. Stratigraphy and structure

In the Aguada de La Cueva Creek area, the Los Sombreros Formation consists of a *c.* 500–600 m thick succession of dominantly limestones, carbonate breccias and conglomerates and subordinate shales (Fig. 2). The limestones are thin bedded, varying from peloidal/calcisphere mudstones and wackestones to graded and laminated calclithites (calciturbidites) (Fig. 3a, b), which may pass upwards into a shale division and gradationally overlie a breccia/conglomerate division. Breccias/conglomerates contain mainly clasts of mudstones, peloidal grainstones and recrystallized limestones, with minor amounts of chert and quartz clasts. They constitute beds that are massive or graded, and that may be gradationally overlain by a calciturbidite; some exceptional examples of stratified (laminated) beds also occur (Fig. 3c). The whole succession lacks *in situ* shallow-water faunas, with the exception of scarce lingulids, and exhibits slight bioturbation restricted to the peloidal/calcisphere limestones. Remarkably, it displays hectometric slump folds, extensional faults and lateral transitions between intact and faulted/brecciated beds (Fig. 3a, d).

As a whole, most of these facies are indicative of sedimentation from gravity flows, from cohesive debris flows to low-density turbidity currents (see Lowe, 1982; McIlreath & James, 1984; Mutti *et al.* 1999, amongst others). Fine-grained, peloidal/calcisphere mudstones probably represent the pelagic/hemipelagic background sedimentation. This interpretation is compatible with the synsedimentary deformation features (see also Section 5.a.1. below), all indicating a slope to base-of-slope setting. The relatively deep-water environment is also suggested by the absence of *in situ* shallow-water fauna and the scarcity of bioturbation.

The slumped succession at the Aguada de La Cueva Creek section is unconformably overlain by grey shales with poorly preserved graptolites, including *Archiclimacograptus* sp., *Dicellograptus* sp., *Dicranograptus* sp., *Nemagraptus* sp. and *Reteograptus speciosus* Harris, which suggest a late Darriwilian to Sandbian age for the upper part of the Los Sombreros Formation in this area (Sample AMGRAP, Figs 2, 4). These graptolitic shales are in turn unconformably overlain by sandstone–mudstone alternations with scarce calcarenites and interbedded conglomerates and calcareous breccias of the Sierra de La Invernada Formation (Furque *et al.* 1990), which are Middle–Late Ordovician in age (Ortega *et al.* 2008).

The Los Sombreros Formation is carried on a W-dipping thrust surface onto the Siluro-Devonian Corralito mélange (Fig. 2), which comprises greenish grey shales and coquinas with extensional features, such as boudins, as well as limestone blocks of the San Juan Formation. The thrust surface displays *C′*-type shear bands and striations, recording an eastward movement of the hanging wall. It is probably Andean in age because it is located at the toe of the Invernada Range and therefore should have been responsible for the uplift of this modern geomorphic feature. However, this thrust could be the result of rejuvenation of an older Chanic or Gondwanic thrust during Andean times, which commonly occurs in the Argentine Precordillera (Ramos, Vujovich & Dallmeyer, 1996; Alonso *et al.* 2005).

5.a.1. Synsedimentary deformation

Regarding the internal structure of the Los Sombreros Formation, the most conspicuous features in the study

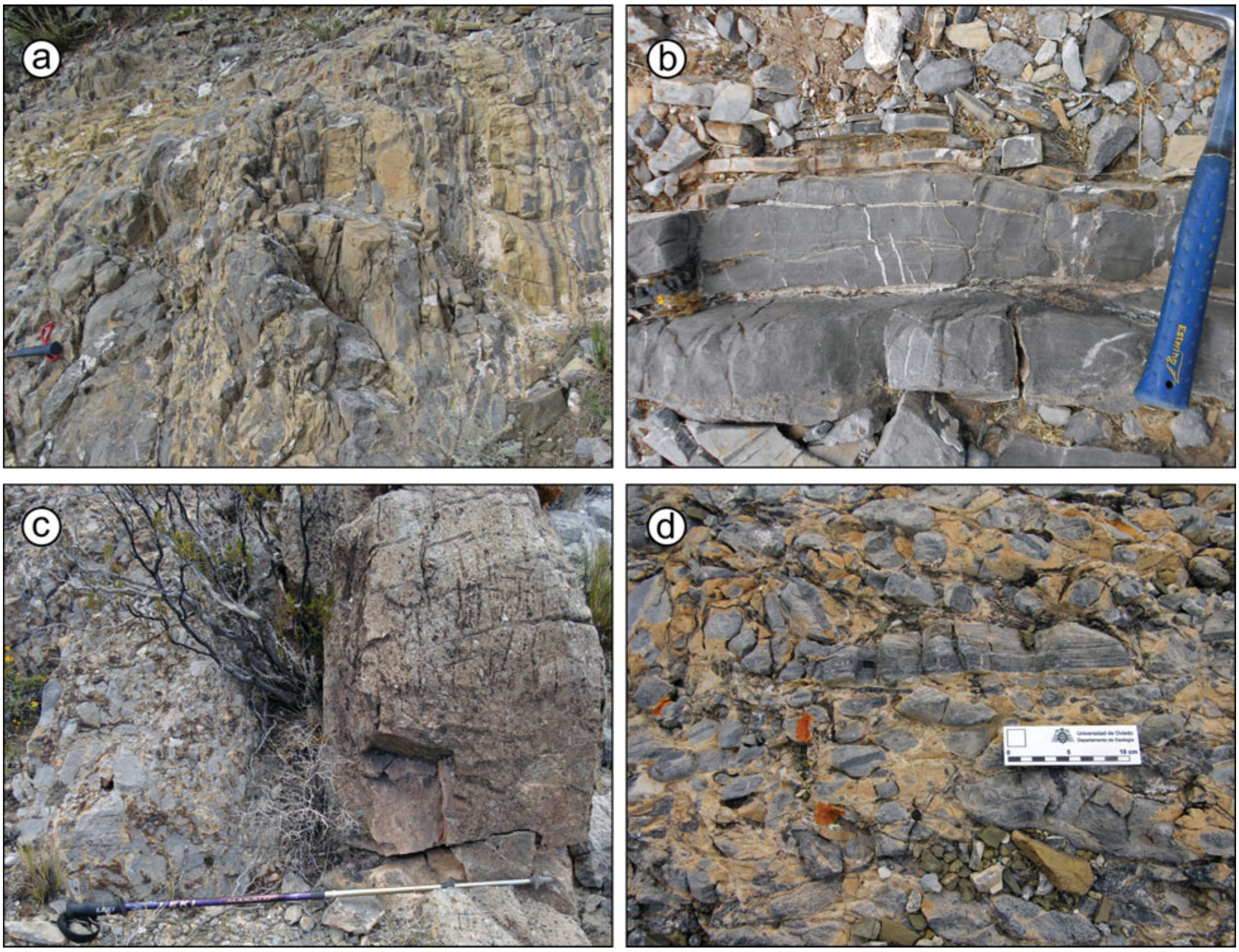

Figure 3. (Colour online) Field photographs of selected deposits from the Los Sombreros Formation at the Agua de la Cueva Creek. (a) Detail of an interval made of pebble-to-cobble breccias (left of photograph) and thin-bedded limestones (laminated mudstones and graded and laminated calciturbidites). Notice the local disruption of bedding, which laterally passes into undisturbed bedding. Stratigraphic top towards the left. (b) Interval formed of calciturbidites and variably laminated, slightly bioturbated mudstones with peloids and calcispheres. The lowermost bed is a graded calciturbidite evolving from a basal fine-pebble-bearing granulestone to a sand-grade division, whose upper part is faintly laminated and displays smooth undulations. Younging direction is to the top of the photograph. Hammer handle for scale *c.* 19 cm long. (c) Poorly sorted boulder-to-pebble carbonate breccia/conglomerate, displaying two divisions, a lower graded division and an upper laminated division. Walking pole is *c.* 120 cm long. Stratigraphic top towards the right. (d) Close-up of an interval made of thin-bedded lime mudstones, commonly laminated, with a variable degree of folding and bed disruption and brecciation. Bedding in the area is parallel to the bed above the scale, which is almost intact. The yellowish matrix surrounding the clasts is mainly dolomitic. Younging direction is to the top of the photograph.

area are hectometric folds that can be interpreted as slump structures (Fig. 2). These folds do not involve the overlying Sierra de La Invernada Formation. As well, most of the smaller, outcrop-scale structures are slump folds with variable hinge-line orientations and pinch-and-swell structures, which record soft-sediment deformation (Fig. 5). Tension fractures perpendicular to bedding and normal faults also occur. In the example of Figure 5a, b, tension fractures are restricted to the yellowish beds, indicating that these beds underwent brittle behaviour, while other beds, with pinch-and-swell boudinage, were stretched by more ductile deformation, probably because the yellowish beds were more lithified. So, pinch-and-swell boudins and tension and shear fractures are more or less coeval and all of them imply bed-parallel extension. Although the development of the slump fold in Figure 5a, b is prior to extensional deformation (both fold limbs are truncated by a normal fault), all the above mentioned structures support the interpretation that gravitational collapse and sliding was the cause of the deformation. In Figure 5d, the cut-off lines of the tension fractures (blue) are parallel to the boudin necks lineation (red), recording the same extension direction.

5.b. Conodont fauna and biostratigraphy

Three carbonate samples taken at the Aguada de La Cueva Creek section yielded conodonts, which constrain the age of the slump deposits of the Los Sombreros Formation with a high-resolution biostratigraphy and improve the conodont biozonation scheme of the Precordillera. The taxonomy of the identified species is well known, following descriptions of previous authors; therefore, only a brief discussion is presented herein.

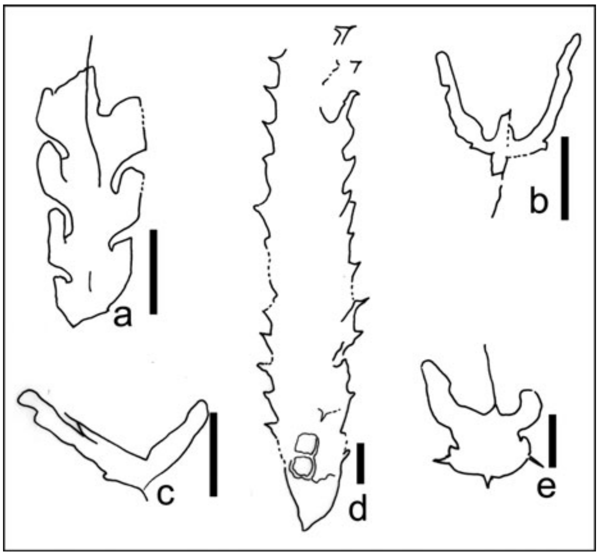

Figure 4. Late Darriwilian to Sanbian graptolites from the upper levels of the Los Sombreros Formation (Sample AMGRAP, see location in fig. 2). (a) *Archiclimacograptus* sp., CORD-PZ 25705; (b) *Dicellograptus* sp., CORD-PZ 25706; (c) *Reteograptus speciosus* Harris, CORD-PZ 25707; (d) *Nemagraptus* sp., CORD-PZ 25708; (e) *Dicranograptus*? sp., CORD-PZ 25709. Scale bar: 1 mm.

A lime mudstone affected by synsedimentary extensional faults (sample AM6) yielded *Cordylodus caboti* Bagnoli, Barnes & Stevens, *C.* cf. *tortus* Barnes, *C. intermedius* Furnish, *C. proavus* Müller, *C.* cf. *andresi* Viira & Sergeyeva, *Drepanoistodus* sp., *Teridontus nakamurai* (Nogami), *Variabiloconus datsonensis* (Druce & Jones), *Westergaardodina* sp. and the index species *Hirsutodontus simplex* (Druce & Jones) (Fig. 6). The latter species is chronostratigraphically restricted to the *Cordylodus intermedius* Zone, Stage 10 of the Furongian. *H. simplex* is characterized by a simple cone with circular cross-section and a series of spines scattered mainly on the anterior and lateral sides of the base and cusp (Fig. 6n).

The different species of *Cordylodus* were distinguished by considering the general shape of the elements, the pattern of denticulation (discrete, confluent) and the basal cavity configuration (number of apices, depth, position and shape of its anterior border). As described by Bagnoli, Barnes & Stevens (1987), the basal cavity of *C. caboti* (Fig. 6g–i) is not as deep as in *C. proavus* (Fig. 6a–e), but also extends above the posterior process. Its basal cavity displays a slightly concave to straight anterior margin that

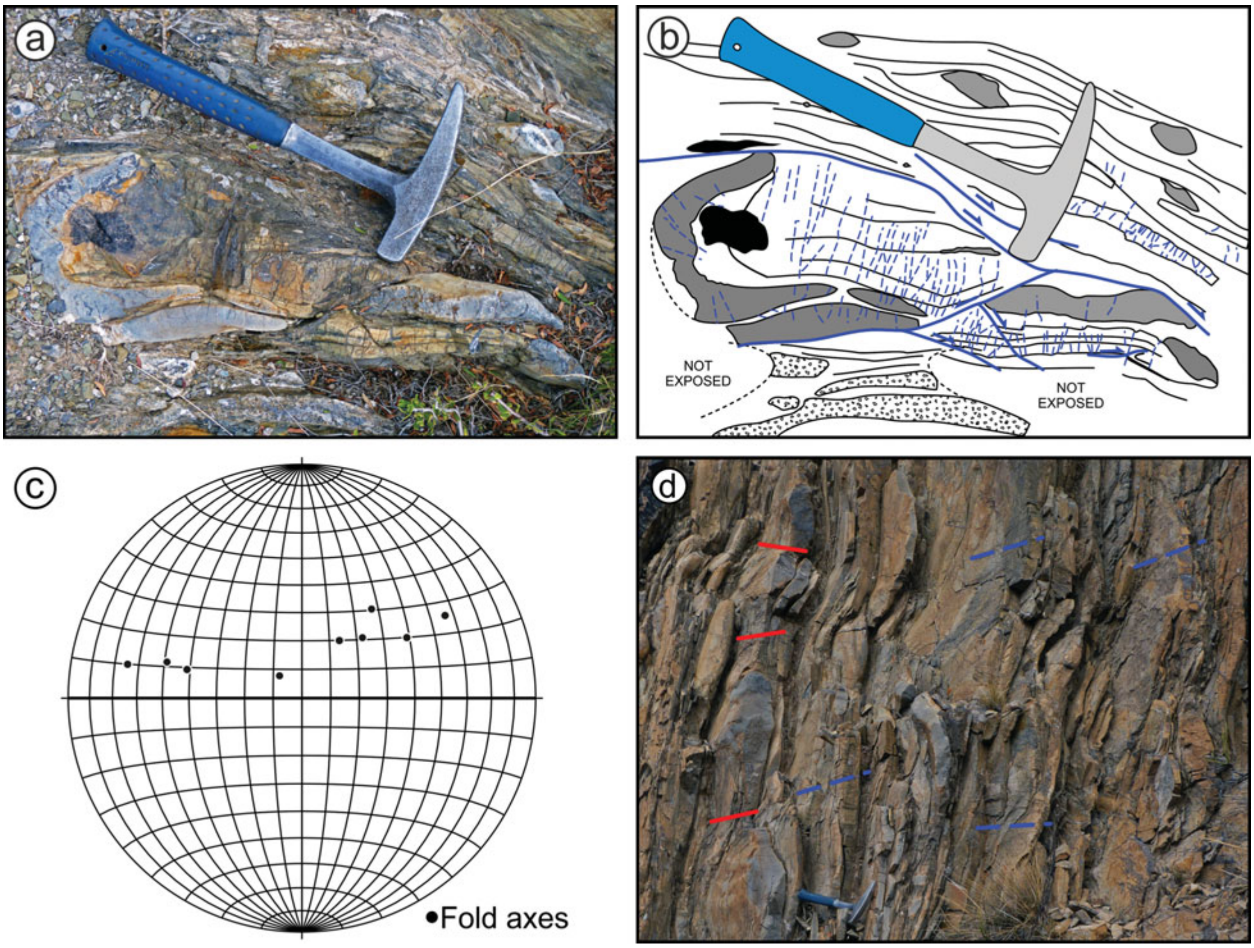

Figure 5. (Colour online) (a, b) Photograph and outcrop sketch showing a slump fold and pinch-and-swell structures in the carbonate succession of the Los Sombreros Formation. Tensional and shear fractures are depicted. See text for explanation, and location in Figure 2. (c) Stereoplot of fold axes in the study area. (d) Boudinaged limestone bed (on the left) and closely spaced microfractures (on the beds located to the right). Hammer for scale: 33 cm.

Figure 6. (Colour online) Conodont elements from the *Hirsutodontus simplex* Subzone of the *Cordylodus intermedius* Zone (upper Furongian, Cambrian), sample AM6: (a–f) *Cordylodus proavus* Müller, (a) S element, lateral view, CORD-MP 50734; (b) S element, lateral view, CORD-MP 50735; (c) S element, lateral view, CORD-MP 50736; (d) P element, lateral view, CORD-MP 50737; (e) S element, lateral view, CORD-MP 50738; (f) S element, lateral view, CORD-MP 50739. (g–i) *Cordylodus caboti* Bagnoli, Barnes & Stevens, (g) S element, lateral view, CORD-MP 50740; (h) S element, lateral view, CORD-MP 50741; (i) S element, lateral view, CORD-MP 50742. (j) *Cordylodus* cf. *tortus* Barnes, S element, lateral view, CORD-MP 50743. (k–m, o, p) *Cordylodus intermedius* Furnish, (k) S element, lateral view, CORD-MP 50744; (l) S element, lateral view, CORD-MP 50745; (m) S element, lateral view, CORD-MP 50746; (o) M element, lateral view, CORD-MP 50747; (p) S element, lateral view, CORD-MP 50748. (n) *Hirsutodontus simplex* (Druce & Jones), CORD-MP 50749, (n1) anterolateral view, (n2) posterior view. (q) *Westergaardodina* sp., lateral view,

curves near the tip, with its apex centrally located, which differentiates it from *C. intermedius* (Nicoll, 1991; Pyle & Barnes, 2002; Zeballo & Albanesi, 2009). Miller *et al.* (2003) regarded *C. caboti* as a junior synonym of *Cordylodus* '*drucei*' Miller; since we cannot follow his criteria in our collection, we maintain the species *C. caboti* as valid.

The *Cordylodus intermedius* Zone is divided into a lower *Hirsutodontus simplex* Subzone and an upper *Clavohamulus hintzei* Subzone (Miller *et al.* 2003). The lower subzone begins with the First Appearance Datum (FAD) of *H. simplex* whereas its top is defined by the FAD of *C. hintzei*. The presence of advanced species of *Cordylodus* in sample AM6, such as *C. caboti* and *C. intermedius*, which are more frequent in the upper subzone, in the absence of *C. hintzei*, suggests an upper *H. simplex* Subzone for this stratigraphic level (e.g. Ross *et al.* 1997).

Cordylodus proavus extends from the upper Cambrian up to the *Iapetognathus* Zone, indicative of the base of the Ordovician, whereas *C. intermedius* and *C. caboti* reach up to the *Rossodus manitouensis* Zone (Pyle & Barnes, 2002). Two elements recovered compare well to the figured forms of *Cordylodus* cf. *andresi sensu* Zeballo & Albanesi (2009) (Fig. 6x), which exhibit a narrower cavity compared to the nominal species (re-illustrated by Miller *et al.* 2015). Additionally, *C. andresi* occurs in older rocks as it is restricted to the *Hirsutodontus hirsutus* and *Fryxellodontus inornatus* zones of the *C. proavus* Zone. *Cordylodus* cf. *tortus* is strongly asymmetric, with a denticle flexed compared to the cusp plane and a basal cavity relatively shallow with its apex slightly displaced to the posterior region (Zeballo & Albanesi, 2009).

The taxonomy of simple cones is complex, particularly owing to their high variability and subtle diagnostic features. *Variabiliconus* shares with *Teridontus* a similar apparatus plan, an abrupt junction between the hyaline base and albid cusp, and the surface microstriation. In particular, *Variabiliconus* (*Oneotodus*) *datsonensis* closely resembles *Teridontus nakamurai* but is distinguished by the circular basal outline, the upturning of the oral termination of the cusp and the presence of shallow furrows associated with carinas (Druce & Jones, 1971; Zeballo & Albanesi, 2009). Miller (1980) reassigned *Oneotodus datsonensis* Druce & Jones to *T. nakamurai* and to *Semiacontiodus nogamii* Miller. Nicoll (1994) rejected the latter suggestion as well as the emended diagnosis given by Ji & Barnes (1994*a*), as they are not applicable to the type species of the genus, which lacks lateral grooves, costae and keels. Tolmacheva & Abaimova (2009) suggested introducing a new genus for hybrid *Teridontus*-like species after further investigations. The limited number of specimens recovered does not allow for adequately defining the latitude of morphologic variability of these primitive forms. Therefore, we cautiously assign a simple subsymmetrical coniform element with long cusp to *T. nakamurai* (Fig. 6u) and those with short, erect and keeled cusps with weak grooves to *V. datsonensis*, which is restricted to the Furongian (Fig. 6w). Younger species of *Variabiloconus* are easier to distinguish as they exhibit an increase of ornamentation and development of the cusp (Löfgren, Repetski & Ethington 1998; Zeballo & Albanesi, 2013*a*). The *Teridontus nakamurai* specimen recovered from the Los Sombreros Formation lacks the typical microstriation of the genus, as previously observed by Lehnert (1994). The genus *Orminskia* also resembles *Teridontus* and lacks microstriation, yet it has a hyaline cusp (Landing, Westrop & Keppie, 2007).

Two samples obtained from thin-bedded fine-grained calciturbidites interbedded with marlstones and breccias located a few metres stratigraphically above AM6 were also productive. Sample AM8A yielded one specimen of *Macerodus dianae* Fåhraeus & Nowlan (Fig. 6s), a distinctive form of the standard North American Midcontinent Realm zonation (Ross *et al.* 1997), whose biostratigraphic range is restricted to a narrow interval of the upper Tremadocian. The *M. dianae* Zone correlates with the lower part of the upper subzone of the *Paltodus deltifer* Subzone of the Baltoscandian scheme (Webby *et al.* 2004). Sample AM8B contains eight elements including *Drepanodus arcuatus* Pander, *Paltodus* aff. *inaequalis* (Pander) (Fig. 6y), *Rossodus* cf. *manitouensis* Repetski & Ethington (Fig. 6r), *Scolopodus* cf. *subrex* Ji & Barnes (Fig. 6t) and a cluster of the paraconodont *Phakelodus tenuis* (Müller). The *S. subrex* Zone partly correlates with the *Macerodus dianae* Zone (Pyle & Barnes, 2002), whereas *Rossodus* cf. *manitouensis* points to a slightly older Ordovician age; yet the available material is not sufficient to verify its taxonomy.

5.c. Conodont palaeoecology and palaeobiogeographic considerations

The recognition of the Furongian *Hirsutodontus simplex* Subzone of the *Cordylodus intermedius* Zone and the Tremadocian *Macerodus dianae* Zone in the Los Sombreros Formation allows the biostratigraphic correlation between the slope facies and the carbonate-platform domain to be improved, as both

CORD-MP 50750. (u) *Teridontus nakamurai* (Nogami), S element, lateral view, CORD-MP 50751. (v) *Drepanoistodus* sp., S element, lateral view, CORD-MP 50752. (w) *Variabiloconus datsonensis* (Druce & Jones), CORD-MP 50753, (w1) lateral view, (w2) basal cavity view. (x) *Cordylodus* cf. *andresi* Viira & Sergeyeva, S element, lateral view, CORD-MP 50754. (r–t, y) Conodont elements from the *Macerodus dianae* Zone (upper Tremadocian, Ordovician): (r) *Rossodus* cf. *manitouensis* Repetski & Ethington, S element, lateral view, sample AM8B, CORD-MP 50755; (s) *Macerodus dianae* Fåhraeus & Nowlan, lateral view, sample AM8A, CORD-MP 50756; (t) *Scolopodus* cf. *subrex* Ji & Barnes, lateral view, sample AM8B, CORD-MP 50757; (y) *Paltodus* aff. *inaequalis* (Pander), lateral view, sample AM8B, CORD-MP 50758. Scale bar: 0.1 mm.

zones occur within the La Silla Formation (Lehnert, Miller & Repetski, 1997). In particular, Albanesi, Cañas & Mango (in press) described thoroughly the conodont association of the *M. dianae* Zone for the shallow-water carbonates of the La Silla Formation, at the Cerro Viejo de San Roque section. *Hirsutodontus simplex*, whose biostratigraphic range is restricted to the *Cordylodus intermedius* Zone, was originally defined in Australia (Druce & Jones, 1971) and subsequently recovered from China (Chen & Gong, 1986; Chen *et al*. 1988), Laurentia (Miller, 1980; Ross *et al*. 1997; Terfelt, Bagnoli & Stouge, 2012; Miller *et al*. 2014), Siberia (Abaimova, 1971, 1975) and NW Argentina (Zeballo & Albanesi, 2009). Miller (1984) suggested that *Clavohamulus* and *Hirsutodontus* had a nektobenthic habit of life and that they preferred warm, shallow seas. The record of *Hirsutodontus* in the Los Sombreros Formation would then indicate reworking of shallow-water deposits into deep-water facies by gravity flows, as observed in the GSSP for the base of the Ordovician at Green Point, Newfoundland (Cooper, Nowlan & Williams, 2001; Miller *et al*. 2014). Accordingly, *Clavohamulus hintzei* Miller, indicative of the upper subzone of *Cordylodus intermedius* Zone, is present in the shallow-marine facies of the La Silla Formation, at the eastern domain of the carbonate platform (Lehnert, Miller & Repetski, 1997).

The species *Teridontus nakamurai* has been found in several lithofacies suggesting a pelagic habit of life (Ji & Barnes, 1994*b*), eventually restricted to the shelf environments owing to a nektobenthic habit (Miller, 1984). After studying a large conodont collection from the Cordillera Oriental, Zeballo & Albanesi (2013*b*) recognized an antithetical relationship between the cosmopolitan genera *Variabiloconus* and *Teridontus*, verifying that the latter predominates in the deeper parts of the platform. In particular, *V. datsonensis* is present in NE Australia (Druce & Jones, 1971), Antarctica (Buggisch & Repetski, 1987) and NW Argentina (Zeballo & Albanesi, 2009).

The genus *Cordylodus* was a major component of most slope and platform communities during Furongian and Early Ordovician times. *C. proavus* has a widespread geographic distribution and is found in a wide range of lithofacies, which suggests a pelagic habit of life. In contrast, *C. andresi*, *C. caboti* and *C. intermedius* preferred deeper-water environments (lower proximal to distal slope facies), as younger species of *Cordylodus* adapted to a nektobenthic mode of life (Miller, 1984; Zhang & Barnes, 2004).

The *C. intermedius* Zone has a wide global distribution and has been documented in China (Chen & Gong, 1986), Laurentia (Bagnoli, Barnes & Stevens, 1987; Barnes, 1988; Miller, 1988; Ross *et al*. 1997; Miller *et al*. 2003) and central Asia (Dubinina, 2000). A correlative conodont assemblage has been retrieved from Australia (Druce & Jones, 1971) and Iran (Müller, 1973). In Argentina, it was previously identified in the Volcancito Formation of the Famatina System (Albanesi *et al*. 2005) and the Cardonal (Rao, 1999) and Santa Rosita formations in the Cordillera Oriental (Zeballo & Albanesi, 2009).

Although conodont provinces can be already distinguished in the late Cambrian (Jeong & Lee, 2000), most of the palaeogeographic studies are concentrated in the Ordovician, when major realms were already established by late Tremadocian times (Miller, 1984; Charpentier, 1984). Accordingly, the Precordillera is identified as a conodont faunal Province of the Temperate Domain of the Shallow-Sea Realm (or the Open-Sea Realm depending on the sedimentary setting) (Albanesi & Bergström, 2010; Serra & Albanesi, 2013), as it lacks the typical shallow-water, tropical forms characteristic of the Laurentian, Australasian or North China provinces (Bagnoli & Stouge, 1991; Zhen & Percival, 2003). Instead, it is distinguished by cosmopolitan or widespread faunas, showing a moderate endemism and diversity when compared with faunas from the Tropical Domain. The Baltoscandian Province of the Cold Domain presents lower diversities and higher abundances instead (Zhen & Percival, 2003).

Macerodus dianae, an index taxon of the late Tremadocian, appeared in sample AM8A. It was first described from outcrops of the Cow Head Group in western Newfoundland, a series of Laurentian slope deposits fed from the outer shelf and the upper continental slope (Fåhraeus & Nowlan, 1978; Pohler, Barnes & James, 1987). Ji & Barnes (1994*a*) emended its diagnosis with material from the Boat Harbour Formation (St George Group) on the Port au Port Peninsula in western Newfoundland. *Macerodus dianae* is recognized in widely separated geographic locations of the Great Basin (Ethington & Clark, 1981; Repetski, 1982; Ross *et al*. 1997; Landing *et al*. 2012), the Arctic Archipelago of Canada (G. S. Nowlan, unpub. Ph.D. thesis, Univ. Waterloo, 1976) and northern Norway (Lehnert, Stouge & Brandl, 2013). In the Kechika Formation of British Columbia, the *Macerodus dianae* Zone is absent and is substituted by the shallow-water *Scolopodus subrex* Zone (Pyle & Barnes, 2002).

Rossodus is a typical genus from the Great Basin, characteristic of the North American Midcontinent Province. The latter is approximately equivalent to the Laurentian Province of the Tropical Domain, in the Shallow-Sea Realm, distinguished by shelf areas < 200 m in depth with high endemism and diversity (Ethington & Clark, 1981; Ross *et al*. 1997; Zhen & Percival, 2003). *Rossodus manitouensis* Repetski & Ethington has also been documented in China (= '*Acodus*' *oneotensus sensu* An, Du & Gao, 1985; Wang, Bergström & Lane, 1996), Korea (Seo, Lee & Ethington, 1994), Thailand (Agematsu *et al*. 2008) and Tasmania (R. C. Cantrill, unpub. Ph.D. thesis, Univ. Tasmania, 2003). It is also known from the peri-Gondwanan volcanic arc of the Famatina System, where it occurs along with *Drepanodus arcuatus*, *Cornuodus longibasis* (Lindström), *Paltodus deltifer pristinus* (Viira), *P. cf. subaequalis* Pander and *Parostodus numarcuatus* (Lindström), which characterize a biofacies dominated by pelagic species from deep/cold waters (Albanesi *et al.* 2005). In the eastern domain of the Precordillera, Lehnert, Miller & Repetski (1997) described *Rossodus* aff. *manitouensis* from shallow-water facies of the La Silla Formation, along with *Alloxoconus* cf. *propinquus* (Furnish), *Scolopodus* cf. *floweri* Repetski, *Paroistodus numarcuatus* and *Colaptoconus quadraplicatus* (Branson & Mehl). The authors correlated this conodont assemblage with the Low Diversity Interval and the lower *Macerodus dianae* conodont biozone in North America (Ross *et al.* 1997), consistent with the suggested age for the samples AM8A and AM8B from the slope facies of the Los Sombreros Formation.

The record of *Macerodus dianae* in the slope facies verifies a strong link between the conodont faunas from the Precordillera with those from Laurentia during Early Ordovician times, demonstrating a connection along the borders of the Iapetus Ocean. Accordingly, Lehnert, Miller & Repetski (1997) interpreted that the record of *Clavohamulus hintzei* in the La Silla Formation as well as the faunal similarities at the species level with the shallow-water North American Midcontinent Province was a consequence of the derivation of the Cuyania Terrane from the Ouachita Embayment in Laurentia. Nevertheless, the conodont faunas do not provide clear evidence to postulate a geographic origin for the Precordillera as they show dominantly Laurentian affinities again in the Middle Ordovician, after a gradual immigration of conodonts from colder regions (Albanesi, 1998; Albanesi & Bergström, 2010).

5.d. Conodont preservation and palaeothermometry

The Cambrian specimens recovered from sample AM6 are well preserved and exhibit a conodont colour alteration index (CAI) 3 that provides some translucency to the conodont elements. The conodonts present smooth surfaces and scarce mineral overgrowths. Microfractures are frequent and are responsible for the lack of apices on cusps and denticles. Conodonts recovered from samples AM8A and AM8B also exhibit a CAI 3 but display a sugary texture with abundant quartz overgrowths instead. In this case, the different type of textural alteration suggests variations in the intensity of the diagenetic processes.

Interestingly, previous findings of reworked pre-Floian conodonts recovered from the Los Sombreros Formation display high CAI values in contrast to the elements recovered from the host rock. This fact was interpreted as a result of burial-related metamorphism and exhumation of the carbonate platform near the suture zone of Cuyania with Gondwana, which supplied detritus to the deep-water basin of the Western Precordillera (Voldman, Albanesi & Ramos, 2009).

The record of Furongian–Lower Ordovician conodonts with CAI 3 (~ 110–200 °C; Epstein, Epstein & Harris, 1977) in the Los Sombreros Formation reflects a simpler burial history instead, if a uniform palaeogeothermal gradient in the basin is considered. A rift-related heat source is not possible to discern as CAI values are relatively low, within the range of the observed values in the platform, which can be accounted for solely by sedimentary burial (Voldman, Albanesi & Ramos, 2010).

Alternatively, the mafic rocks from the Western Precordillera produced very restricted thermal anomalies in the country rocks given the small volume of single-pulsed basalt intrusions, which could only slightly contribute to a regional increment of the heat flux (Voldman, Albanesi & do Campo, 2008; González-Menéndez *et al.* 2013). This is consistent with the metamorphic conditions inferred from the paragenetic associations of the mafic rocks, which suggests *c.* 250–350 °C and 2–3 kbar, with palaeogeothermal gradients of ~ 30–35 °C km^{-1} (Robinson, Bevins & Rubinstein, 2005), which are typical of mature passive margins and foreland basins (e.g. Allen & Allen, 2005). Consequently, the CAI 3 in the studied conodont samples reflects a thermal history related to the sedimentary burial and nappe stacking of the Western Precordillera.

6. Conclusions

The new conodont data from the Los Sombreros Formation in La Invernada Range along with the sedimentological and structural analysis carried out in the study area show that slope sedimentation and gravity sliding has taken place in the Precordillera since at least late Cambrian times, contrasting with the current hypothesis of a Devonian age for the slope deposits of the Los Sombreros mélange. Moreover, the recognition of the *Hirsutodontus simplex* Subzone of the *Cordylodus intermedius* Zone (upper Furongian, Cambrian) and the *Macerodus dianae* Zone (upper Tremadocian, Ordovician) improves the correlation with the La Silla Formation of the Precordilleran carbonate platform as well as with regions of Gondwana and other palaeocontinents. The record of the index species *Macerodus dianae* in the Los Sombreros Formation, as well as *Clavohamulus hintzei* in the La Silla Formation, emphasizes the strong faunal affinity of the shelf environments of the Precordillera with the Laurentian Province of the Tropical Domain for the late Cambrian – Early Ordovician periods. However, given the wide global distribution of the studied specimens, the present data are not indicative of a geographic origin for the Precordillera. The thermal alteration of the studied specimens is consistent with the sedimentary burial and nappe stacking of the Western Precordillera.

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